Postprint of Narrow-band Optical Imaging Observations and Analysis of MASTA and WFST Wide-field Telescopes

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Abstract

In optical systems with small focal ratios, the optical performance of narrowband filters is significantly affected by the telescope' s optical system and the angle of incidence of light. From the center to the edge of the field of view, the angular deviation of the incident light gradually increases, causing narrowband filters to exhibit a blue shift in central wavelength, broadening of the passband, and attenuation of maximum transmittance. To address the need for narrowband survey observations with the WFST (Wide Field Survey Telescope) and MASTA (Multi-Application Survey Telescope Array) telescopes, we quantitatively analyze the variation of central wavelength and passband of different narrowband filters as a function of field radius. WFST has a focal ratio of $ F/2.49, withamaximumoff − axisangleofincidenceof13.27^{ }.Atthepointofmaximumdeviation, narrowbandfilterswithcentralwaveleng and 41.80%, respectively. The maximum transmittance attenuation coefficients are 80.00% and 74.50%, respectively. The MASTA telescope has a focal ratio of $ F/1.74, withamaximumoff−axisangleofincidenceof18.48^{ }.Atthepointofmaximumdeviation, thecentr and 81.70%, respectively, and the maximum transmittance attenuation coefficients will be 80.00% and 63.90%, respectively. For future narrowband observations of emission lines or absorption lines based on WFST and MASTA, it is necessary to systematically consider the effects of central wavelength blue shift and passband broadening.

Full Text

Preamble

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Analysis of Narrow-band Optical Imaging Observations for MASTA and WFST Wide-field Telescopes

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Abstract

In optical systems with small focal ratios, the performance of narrow-band filters is significantly affected by the telescope's optical design and the angle of incident light. From the center to the edge of the field of view, the increasing deflection of the incident angle causes a blue shift in the central wavelength, broadening of the bandpass, and attenuation of the maximum transmittance in narrow-band filters. To meet the requirements for narrow-band survey observations with WFST (Wide Field Survey Telescope) and MASTA (Multi-Application Survey Telescope Array), we quantitatively analyze how the central wavelength and bandpass of different narrow-band filters vary with field radius.

WFST has a focal ratio of 2.49 and a maximum off-axis incident angle of 13.27°. At maximum deflection, narrow-band filters with central wavelengths of 395 nm and 656 nm exhibit a maximum central wavelength blue shift of 0.78 Å, with the 10 nm and 1 nm bandpasses increasing by 2.67 Å and 41.80 Å, respectively. The maximum transmittance attenuation coefficients are 80.00% and 74.50%. MASTA has a focal ratio of 1.74 and a maximum off-axis incident angle of 18.48°. At maximum deflection, narrow-band filters with central wavelengths of 395 nm and 656 nm show a central wavelength blue shift of 2.70 Å, with the 10 nm and 1 nm bandpasses broadening to 4.20 Å and 81.70 Å, respectively. The maximum transmittance attenuation coefficients are 80.00% and 63.90%. Future narrow-band observations of emission or absorption lines with WFST and MASTA must systematically account for these effects of central wavelength blue shift and bandpass broadening.

Keywords: telescopes, instrumentation: filter, techniques: photometers, wide-field imaging

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1 Introduction

Narrow-band surveys, which target specific emission lines using narrow-band filters, are widely employed in astronomical research. Compared to spectroscopic observations, narrow-band photometry efficiently measures the intensity of target emission lines for numerous objects across wide fields, enabling efficient selection of specific emission-line sources. Additionally, the sky background in the corresponding optical band is typically lower, facilitating the detection of fainter emission-line signals. Currently, several telescopes worldwide equipped with wide-field cameras have endowed optical narrow-band surveys with powerful observational capabilities.

For observations within the Milky Way and nearby galaxies, narrow-band imaging can study emission-line nebulae, including the spatial distribution of HII regions, planetary nebulae, Herbig-Haro (H-H) objects, and supernova remnants. These studies provide rich information about star formation and evolution. For instance, HII regions effectively trace star-forming regions, and since ionized gas often exhibits strong Hα emission, photometric measurements of this line serve as a primary method for probing both local and global star formation in galaxies. Planetary nebulae are commonly detected through strong [OIII] doublet and Hα lines, with the MASH (The Macquarie/AAO/Strasbourg Hα Planetary Nebula Catalogue) providing numerous samples for subsequent research [1]. H-H objects can be identified by combining [SII] and Hα lines, tracing outflows near young stars and indicating active star formation [2–4]. Supernova remnants reflect the properties of their progenitor stars. Since supernova explosions are brief events, observations alone cannot fully characterize the final stages of stellar evolution. Supernova remnants help complete our understanding of stellar evolution and constrain the physical properties of any associated central compact objects [5–6].

Narrow-band observations also efficiently identify and confirm emission-line galaxies at medium to high redshifts. Based on sufficiently large samples of emission-line galaxies, valuable galaxy parameters such as emission-line luminosity functions can be obtained. Galaxy luminosity functions are commonly fitted using the Schechter function [7], which describes the distribution of galaxy numbers within specified luminosity intervals. Luminosity functions provide information about galaxy environments—whether in clusters or general fields—and the distribution of different galaxy types within samples, particularly when telescope resolution is insufficient for morphological classification [8–11]. Comparing luminosity functions with other galaxy characteristic functions yields additional insights; for example, comparison with stellar mass functions can reveal relationships between stellar mass and star formation rate within given redshift ranges [12–13]. Different emission lines vary in dust absorption intensity and production mechanisms, and comparing these differences provides richer information than single emission lines alone. For instance, comparing Lyα and Hα luminosity functions can analyze galaxy dust structures and morphological feature distributions [14–15]. Galaxy parameters evolve with redshift, and comparing luminosity functions of the same emission-line galaxy type at different redshifts reveals how stellar population characteristics change with cosmic evolution [16–18].

Many characteristic emission lines are crucial for high-redshift galaxy studies, with Lyα being particularly representative as the strongest emission line. Since Partridge and Peebles [19] first highlighted the importance of Lyα for high-redshift galaxy research, numerous observational studies have been conducted [20–22]. Early emission-line studies were limited by telescope capabilities, constrained by small apertures and fields of view, yielding results for only small areas and limited samples. This limitation motivated the development of large-aperture, wide-field telescopes. In recent years, the construction of such telescopes has significantly expanded the depth and breadth of emission-line research. Large apertures ensure high-sensitivity detection of faint signals, while wide fields enable systematic observations of large-scale structures and large samples, advancing emission-line studies considerably. During the cosmic noon at redshifts z 2–3, Lyα emission from celestial objects redshifts into the optical band, allowing detection with optical narrow-band filters. This epoch, characterized by rapid formation of massive galaxies and cosmic structures with peak star formation and AGN activity, is ideal for studying galaxy evolution in relation to cosmic environment. Large samples of emission-line galaxies can reveal the large-scale structure of protoclusters and predict their future evolution [23–26]. Additionally, extended Lyα-emitting structures known as Lyα blobs/nebulae effectively trace ionized intergalactic medium, and their distribution can map the structural characteristics of intergalactic media in galaxy clusters, which trace the evolution of cosmic large-scale structures [27]. For the reionization epoch ($z > 6$), Lyα emission also provides rich scientific information, as Lyα photons are easily resonantly scattered by neutral hydrogen, making this emission an excellent tracer of ionization conditions in neutral interstellar medium during reionization [28].

Similar to Lyα, Hα emission lines can also identify high-redshift galaxies [29] and trace star formation rates. For example, the HiZELS (The High-z Hα Emission Line Survey) [30] provided Hα luminosity functions and star formation rates for large samples of emission-line galaxies at different redshifts.

Combined with the capabilities of new-generation wide-field survey telescopes, a series of narrow-band observational projects have been or are being planned. Some observations targeting objects within the Galaxy and nearby galaxies focus on star formation and evolution, spatially resolved distributions of star-forming regions, planetary nebulae, and stellar population properties of globular clusters, such as S-PLUS (The Southern Photometric Local Universe Survey) [31] and BNBIS (The Byurakan Narrow Band Imaging Survey) [3–4]. Other programs targeting medium to high-redshift galaxies focus on luminosity function evolution of different emission lines, differences in galaxy properties across environments, protocluster structures, and their correlation with dark matter halos, such as SILVERRUSH (Systematic Identification of LAEs for Visible Exploration and Reionization Research Using Subaru HSC) [32], SFACT (The Star Formation Across Cosmic Time) [33], and ODIN (The One-hundred-deg^2 DECam Imaging in Narrowbands) [34]. Wide-field survey facilities provide vast amounts of data; for instance, HSC with its 1.7° diameter field of view acquires nearly 1 TB of data per night. Next-generation survey telescopes such as LSST (The Large Synoptic Survey Telescope), Roman (The Nancy Grace Roman Space Telescope), and the Wide Field Survey Telescope (WFST) designed by Purple Mountain Observatory offer even larger fields of view and higher observational efficiency. Taking WFST as an example, this telescope has a 2.5 m aperture, f/2.49 focal ratio, and 3° diameter field of view. Its ongoing survey plans include wide-field observations covering approximately 8000 deg^2, with high-frequency deep fields covering 1000 deg^2. Over a 6-year planned observation period, it will reach limiting magnitudes about 2 mag deeper than SDSS (Sloan Digital Sky Survey). Advantages of wide fields include more efficient and comprehensive monitoring of time-domain signals such as AGN variability, tidal disruption events (TDEs), and supernova explosions. Another advantage is the ability to conduct deep observations of large-scale structures and matter distributions; stacked wide-field data enable better cosmological studies such as gravitational lensing and galaxy cluster formation [35–37].

Due to emission-line contributions, strong emission-line targets exhibit significantly higher measured flux in narrow-band observations than in broadband observations, enabling the discovery of high-redshift emission-line galaxies with narrow-band imaging. However, in most cases, such filters have bandpasses wider than typical emission-line widths, and their transmittance varies substantially across the bandpass, leading to large uncertainties in derived redshifts and fluxes from a specific narrow-band filter observation [38]. To address this issue, more accurate redshift and flux estimates can be determined from flux ratios observed with different narrow-band filters and several matching broadband filters.

Particularly in optical systems with large focal ratios, narrow-band imaging is significantly affected by the telescope' s optical system and the angle of incident light. In this study, we analyze how the optical performance parameters of narrow-band filters vary with field angle for two wide-field telescopes—WFST and MASTA (Multi-Application Survey Telescope Array)—using the blue-end 395 nm and r-band 656 nm narrow-bands as examples, providing quantitative results to support future narrow-band observations.

2 Principles of Narrow-band Filters

Table 1 lists several commonly used narrow-band wavelengths and their corresponding emission lines and observational targets. Narrow-band observations are also frequently used to identify emission-line galaxies within specific redshift ranges, such as Lyα emitters. The table also includes corresponding Lyα redshift values for several bands.

Table 1 Commonly used narrowband filters with their corresponding observational targets

Wavelength (nm)	Emission Line	Primary Targets	Lyα Redshift
372.7	[OII]	Star-forming regions and galaxies	-
395.0	-	Cool stars (M dwarfs, brown dwarfs)	2.24
495.9	[OIII]	Emission nebulae	-
500.7	[OIII]	Planetary nebulae, supernova remnants	-
656.3	Hα	Emission nebulae, star-forming regions	4.40
673.0	[SII]	Supernova remnants, H-H objects	-

Currently, most widely used narrow-band filters are based on all-dielectric filters, which are multi-layer Fabry-Pérot interferometers with each layer thickness being an integer multiple of one-quarter the central wavelength [39]. This type of narrow-band filter can be equivalently modeled as a sandwich structure with two interfaces [40–41], making calculations of transmittance and bandpass parameters more straightforward.

For all-dielectric filters, the wavelength of maximum transmittance satisfies:

$$2nd\cos\theta = m\lambda \tag{1}$$

where n is the refractive index of the spacer layer, θ is the effective incident angle, d is the spacer layer thickness, λ is the incident light wavelength, and m is a positive integer. According to Snell' s law, if the refractive index outside the filter equals 1, then $n\sin\theta = \sin\theta_0$, where θ_0 is the incident angle of the incoming light.

The relationship between central wavelength shift $\Delta\lambda$ and incident angle θ satisfies [42]:

$$\Delta\lambda = \lambda - \lambda_0 = \lambda_0\sqrt{1-\frac{\sin^2\theta}{n^2}} \approx -\frac{\lambda_0\sin^2\theta}{2n^2} \approx -\frac{\lambda_0\theta^2}{2n^2} \quad (\text{if } \theta \ll 1) \tag{2}$$

where λ_0 refers to the original central wavelength.

In actual telescope optical systems, the beam incident on the filter is not parallel light at a fixed angle but rather a converging beam with a half-angle θ (related to the system' s focal ratio) illuminating the focal plane. Consequently, each point on the focal plane integrates light from a range of incident angles. Analysis must therefore be based on the imaging beam characteristics of the optical system. Assuming the filter is placed in this converging light path with its surface normal (or optical axis) perpendicular to the filter plane, and the beam' s half-aperture angle is θ, the relationship between bandpass width variation and incident angle under these conditions can be described by:

$$\frac{\Delta\lambda}{\Delta\lambda_0} = (1 + X^{1/2}) \quad \text{where } X = \frac{F^{1/2}}{B^2} \tag{3}$$

where $\Delta\lambda$ is the filter' s bandpass when illuminated by converging light with half-angle θ, $\Delta\lambda_0$ is the ideal bandpass for perfectly parallel light, and B is a parameter related to specific coating parameters. Detailed calculation methods for these parameters are provided in the work of Lissberger et al. [40–41].

When light is incident at an angle, its optical path length within the coating layers increases, causing the filter' s peak transmittance to decrease. In practical optical systems, the chief ray from both central and edge field regions has different incident angles relative to the system optical axis. Oblique incidence results in effective optical path lengths significantly greater than the physical thickness of the layers, with different incident angles corresponding to different increments in effective optical path length. These combined effects ultimately cause a blue shift in the filter' s central wavelength and broaden and distort its transmission spectrum.

The above analysis and formulas for bandpass variation apply to parallel (collimated) beams with specific incident angles. However, in actual telescope systems, each image point on the focal plane represents the integrated result of light within its corresponding incident angle range. [Figure 1: see original paper] illustrates the range of incident light angles for each image point on the focal plane. Notably, the distribution of incident angle ranges differs subtly between central and edge field points, covering all possible incident angles. Therefore, reliable results must be calculated based on the actual range of incident angle variations to determine changes in filter optical performance (such as bandpass width and central wavelength). Furthermore, while the central wavelength shift equation applies to a single incident angle, for image points in a real converging beam (covering a range of incident angles), this relationship must be integrated to obtain the effective optical performance of the filter at that image point.

Equation (3) calculates the coefficient for narrow-band filter bandpass variation. For a specific point on the focal plane, the integrated average over the angular range must be computed. Referring to equation (4), using the telescope's optical system parameters, we can calculate the range of incident angles on the filter for light converging to image points on the focal plane, including both on-axis and off-axis points:

$$\Delta\lambda_{eff} = \int_{\theta_1}^{\theta_2} [1 + X(\theta)^{1/2}]\Delta\lambda_0 \, d\theta/\Delta\theta \tag{4}$$

where $\Delta\theta = \theta_2 - \theta_1$.

Incident angle deflection affects filter transmittance, bandpass width, and central wavelength. Following the methods of Lissberger et al. [40–41] and Zheng et al. [42], we simulated the optical parameters of filters under different incident angle offsets.

The filter’ s central wavelength shifts toward the blue with increasing angle of incidence (AOI). This shift depends only on the original central wavelength and incident angle magnitude, independent of bandpass characteristics. [Figure 2: see original paper] shows how the central wavelength shift varies with incident angle for filters with different central wavelengths.

[Figure 3: see original paper] compares the bandpass variation characteristics of 1 nm and 10 nm bandpass filters under changing parallel light incident angles. Bandpass width shows low sensitivity to incident angle changes, with observable variations only at large incident angles and extremely narrow original bandpasses (1 nm), where increasing incident angle causes slight broadening. Peak transmittance attenuation depends on both the original central wavelength and bandpass—longer wavelengths and narrower bandpasses result in greater attenuation.

3.1 WFST Narrow-band Optical Performance

WFST is a wide-field survey telescope designed and built for large-area surveys. The telescope’ s optical structure is described in Lou et al. [43], and its main specifications are listed in **Table 2** .

Table 2 Specifications for WFST

Specification	Value
Aperture	2.5 m
Field of View (FOV)	3° diameter
Focal Ratio	2.49
Etendue	
Wavelength Range	320–960 nm
Image Quality	
Blinding	
Pointing Tracking (One loop, 1 min)	$ $0.4

WFST’ s primary mirror has a 2.5 m aperture with an f/2.49 focal ratio. In its optical system, the maximum incident angle deviation at the field edge is 13.27°, whose effects cannot be ignored. For central wavelengths (CWL) of 395 nm and 656 nm, we consider filters with 10 nm and 1 nm bandpasses (i.e., 395 nm/10 nm, 656 nm/1 nm). [Figure 4: see original paper] shows the simulated transmittance changes of these filters under collimated light conditions at different incident angles from the field center to edge. Here, the filter bandpass is defined as the full width at half maximum (FWHM) of the simulated transmittance curve.

3.2 MASTA Narrow-band Optical Performance

The Multi-Application Survey Telescope Array (MASTA) is primarily used for searching and discovering large numbers of medium-to-high-orbit space debris. **Table 3** provides the main specifications for a single telescope in the array.

Table 3 Specifications for MASTA

Specification	Value
Optical Design	Prime Focus
Aperture	710 mm
Focal Length	1238 mm
Focal Ratio	1.74
Detector Resolution	8k × 8k
Maximum Quantum Efficiency	

This telescope has a 710 mm aperture, 1238 mm focal length, and f/1.74 focal ratio. Compared to WFST, MASTA exhibits larger incident angle deflection at the field edge, with a maximum off-axis incident angle deviation of 18.48°. For central wavelengths of 395 nm and 656 nm, we again consider 10 nm and 1 nm bandpass filters (395 nm/10 nm, 656 nm/1 nm). [Figure 5: see original paper] shows the simulated transmittance changes under collimated light conditions at different incident angles from field center to edge.

Table 4 shows the on-axis versus off-axis converging beam angle ranges and corresponding bandpass variation coefficients for both optical systems, while **Table 5** presents the relationship between blue-end shift of the central wavelength and incident angle.

Table 4 On-axis vs. off-axis incidence angle differences and bandpass variation in telescopes

Telescope	Bandpass/Position	Incident light angle (°)	Bandpass changed (%)
WFST	on-axis	0–11.89	0
	off-axis	1.78–13.27	2.67

Telescope	Bandpass/Position	Incident light angle (°)	Bandpass changed (%)
MASTA	on-axis	0–16.66	0
	off-axis	4.57–18.48	4.17

Table 5 Relationship between blue-end shift of central wavelength and incidence angle

Telescope	Central wavelength (nm)	Max incident angle (°)	Wavelength shift (%)
WFST	395	13.27	0.20
	656	13.27	0.12
MASTA	395	18.48	0.68
	656	18.48	0.41

The simulation results demonstrate that WFST’ s f/2.49 focal ratio yields a maximum off-axis incident angle of 13.27°. At this extreme, narrow-band filters at 395 nm and 656 nm experience a central wavelength blue shift of 0.78 Å, with the 10 nm and 1 nm bandpasses broadening by 2.67 Å and 41.80 Å, respectively. The maximum transmittance attenuation values are 80.00% and 74.50%. In contrast, MASTA’ s f/1.74 focal ratio results in a maximum off-axis incident angle of 18.48°. At maximum deflection, the central wavelengths at 395 nm and 656 nm blue shift by 2.70 Å, with the 10 nm and 1 nm bandpasses broadening to 4.20 Å and 81.70 Å, respectively. The maximum transmittance attenuation coefficients are 80.00% and 63.90%.

Since on-axis and off-axis cases encompass all possible light incident angles, we can determine the range of bandpass variation for narrow-band filters in both telescopes. For WFST, a filter with an original 10 nm bandpass will not exceed 2.67 Å after variation, while a 1 nm bandpass filter will not exceed 41.80 Å. For MASTA, a 10 nm bandpass filter will not exceed 4.17 Å, and a 1 nm bandpass filter will not exceed 81.70 Å.

3.3 Impact of Narrow-band Filter Optical Performance Changes

Based on simulations for both telescope systems, we can estimate the redshift deviation when identifying high-redshift targets. For Lyα emitters observed with a 395 nm central wavelength filter, the target galaxy’ s redshift should be approximately z = 2.24. In WFST, the maximum 0.78 Å wavelength blue shift would shift the target redshift to z = 2.22, corresponding to a distance reduction of 26.5 Mpc. In MASTA, the maximum 2.70 Å blue shift would shift the redshift to z = 2.16, reducing the distance by 107.6 Mpc.

According to the analytical relationship between filter central wavelength shift and light incident angle, the shift $\Delta\lambda$ depends strictly on the optical system' s focal ratio and the filter medium' s refractive index n (which together determine the maximum half-angle θ_{max}). Consequently, the observed target redshift offset Δz is also completely determined by these parameters. Taking a Lyα emission source at 1216 nm as an example: when observed with a 395 nm narrow-band filter, the theoretical detection wavelength $\lambda_{obs} = 399.8$ nm. [Figure 6: see original paper] quantitatively shows how measured redshift varies with incident angle, demonstrating that telescopes with smaller focal ratios exhibit larger redshift measurement offsets.

If uncorrected narrow-band filters are used to observe targets with an original redshift estimate of z = 2.24, the combined effects of central wavelength shift, bandpass broadening, and peak transmittance attenuation will significantly distort observational results. [Figure 7: see original paper] shows the transmittance curves of narrow- and broadband filters alongside the simulated spectral energy distribution (SED) of an emission-line source. It clearly illustrates that the shifted filter transmission profile no longer matches the emission-line profile, causing the target signal to fall outside the effective bandpass coverage.

Comparing broadband and narrow-band photometric data for the same target is a common method for identifying emission-line objects. When narrow-band filter transmittance curves shift and broaden, the excess of narrow-band photometric values over broadband values decreases significantly, reducing the signal-to-noise ratio of photometric observations. By convolving the simulated filter transmittance curves with the target' s energy spectrum, we can obtain relative flux magnitudes for broadband and narrow-band photometry as follows:

$$L_{relative} = \frac{\int f_{filter}(\lambda) \times f_{target}(\lambda)\, d\lambda}{\int f_{filter}(\lambda)\, d\lambda} \tag{5}$$

where f_{filter} and f_{target} refer to the filter transmittance curve and the target' s spectral energy distribution, respectively. We selected simulated data for a broadband filter covering 395 nm with a 150 nm bandpass and compared it with narrow-band photometry results before and after offset. The results show that for a 10 nm, 395 nm filter installed on MASTA, the relative photometric flux is 204.05, decreasing to 197.30 after transmittance curve shift, while the broadband relative photometric flux is 180.04. This demonstrates that narrow-band photometry results are indeed affected.

As incident angle increases, the filter' s central wavelength experiences a blue shift while peak transmittance decreases, causing mismatch between the target spectrum and the filter' s nominal response and reducing effective signal intensity. Additionally, oblique incidence increases filter reflection losses and scattering noise, further degrading signal-to-noise ratio. Taking a 656 nm filter as an example for a target with magnitude 20, we calculated SNR variations using WFST telescope and camera parameters, primarily through simulation analysis with the DECam exposure time calculator, assuming new moon sky background conditions. When the incident angle increases from 0° to 18°, the filter' s peak transmittance decreases by approximately 20.0%, corresponding to an SNR reduction of about 21.7%. This effect is particularly significant in wide-field photometry, requiring angle-dependent correction factors in observation planning and data processing to compensate for SNR loss and ensure consistent data quality. **Table 6** shows how narrow-band observation SNR changes with increasing incident angle.

Table 6 Analysis of incidence angle impact on signal-to-noise ratio in narrow-band photometry

AOI (°)	SNR (dB)	SNR retention (%)
0		100
6		95.2
12		88.7
18		78.3

Note: measurement conditions: wavelength (656 ± 10) nm, integration time 90 s.

Considering both SNR degradation and photometric flux measurement bias, and following the general procedure for identifying emission-line galaxies, we estimated the fraction of targets that might be misidentified as false sources. Following the criteria from An et al. [13], emission-line galaxy sources are selected using:

$$(NB - BB) > \Sigma\sqrt{\sigma_{NB}^2 + \sigma_{BB}^2}, \quad EW > 50\text{Å} \tag{6}$$

where NB and BB represent narrow-band and broadband photometric magnitudes, σ_{NB} and σ_{BB} are sky background noise in narrow-band and broadband observations, Σ ranges from 2 to 3, and EW is the equivalent width derived from flux differences. The EW measurement is influenced by sample selection criteria; different color selections or narrow/broadband threshold settings lead to different EW distributions. This equivalent width selection criterion converts to a magnitude difference of $(BB - NB)_{EW=50\text{Å}} = 0.77$.

Based on this criterion, we used Monte Carlo methods to simulate broadband and narrow-band photometric data for 1000 emission-line sources, calculating the fraction of successfully identified sources before and after SNR and photometric flux effects. In this criterion, the affected parameters are narrow-band photometric magnitude NB and background sky noise term σ_{NB}. [Figure 8: see original paper] and [Figure 9: see original paper] plot the color-magnitude diagrams for selecting emission-line sources before and after parameter changes, indicating the fraction of identified emission-line sources relative to all sources.

The simulation results demonstrate that the susceptibility of narrow-band filters to incident angle variations leads to SNR degradation and offset in narrow-band photometric magnitudes, reducing the identification rate when actually confirming emission-line galaxies and significantly decreasing sample identification accuracy.

Overall, the combined effects of central wavelength blue shift and bandpass broadening substantially degrade the observational quality of emission-line objects. Bandpass broadening directly increases the dispersion in redshift measurements of emission-line objects, significantly weakening the statistical reliability of galaxy cluster membership identification. Meanwhile, the blue-shifted central wavelength combined with broadened bandpass introduces stronger continuum noise from sky background, causing systematic selection bias in emission-line galaxy samples.

4 Summary

We have analyzed and presented the variation of narrow-band filter transmittance parameters with light incident angle from field center to edge for the WFST and MASTA optical systems. WFST has an f/2.49 focal ratio with a maximum off-axis incident angle of 13.27°. At maximum deflection, narrow-band filters at 395 nm and 656 nm experience a central wavelength blue shift of 0.78 Å, with 10 nm and 1 nm bandpasses broadening by 2.67 Å and 41.80 Å, respectively. Maximum transmittance attenuation values are 80.00% and 74.50%. MASTA has an f/1.74 focal ratio with a maximum off-axis incident angle of 18.48°. At maximum deflection, the central wavelengths at 395 nm and 656 nm blue shift by 2.70 Å, with 10 nm and 1 nm bandpasses broadening to 4.20 Å and 81.70 Å, respectively. Maximum transmittance attenuation coefficients are 80.00% and 63.90%.

Based on these results, WFST's incident angle deflection has minimal impact on filter optical performance when using 10 nm narrow-band filters, with perceptible effects only for longer target central wavelengths where blue shift may become noticeable. Due to its smaller focal ratio, MASTA exhibits significantly larger central wavelength shifts than WFST under the same conditions, so narrow-band target observations—such as identifying emission-line galaxies using broadband/narrow-band flux differences—will be more substantially affected. For 1 nm bandpass narrow-band filters, transmittance attenuation and bandpass broadening are much more pronounced, meaning ultra-narrow-band filters are more severely impacted.

In actual filter production and installation, coating designs can be adjusted to modify the final transmittance curve. For example, the designed bandpass range can be appropriately shifted toward the red end, making the target central wavelength longer and the target bandpass narrower in the initial design, so that actual optical performance better matches design requirements.

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